The age of Upper Scorpius from eclipsing binaries

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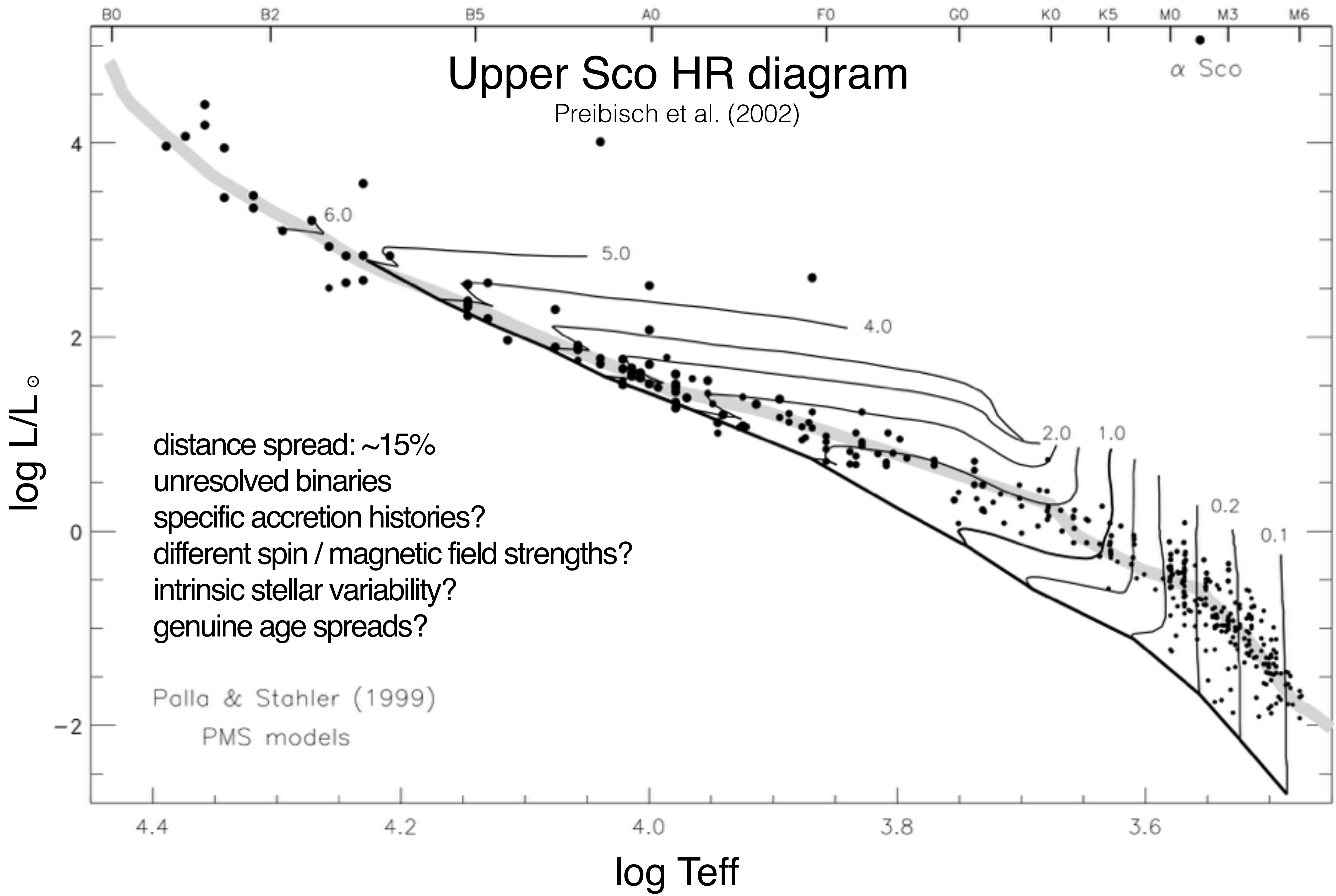
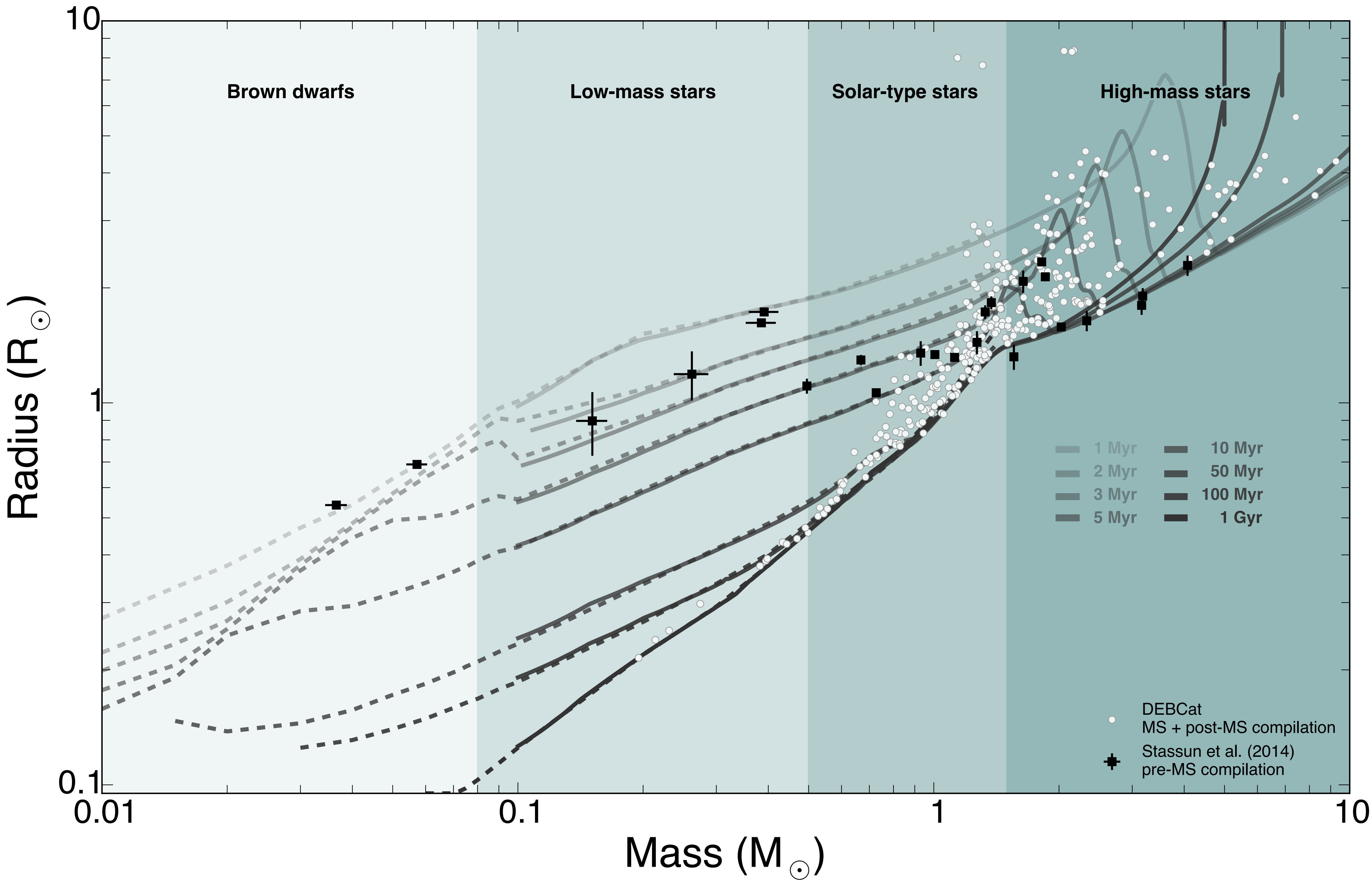
Upper Sco HR diagram

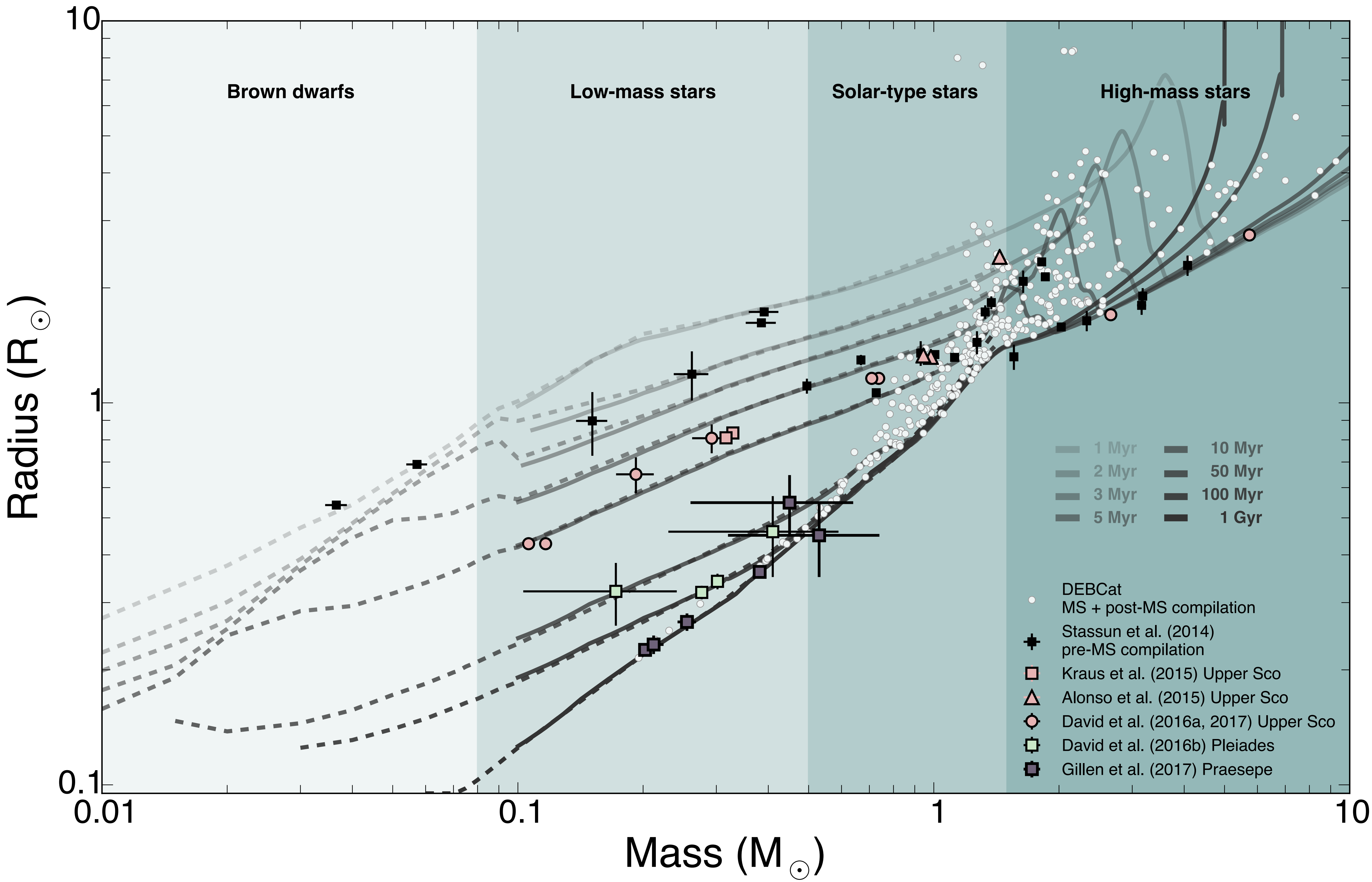
Preibisch et al. (2002)

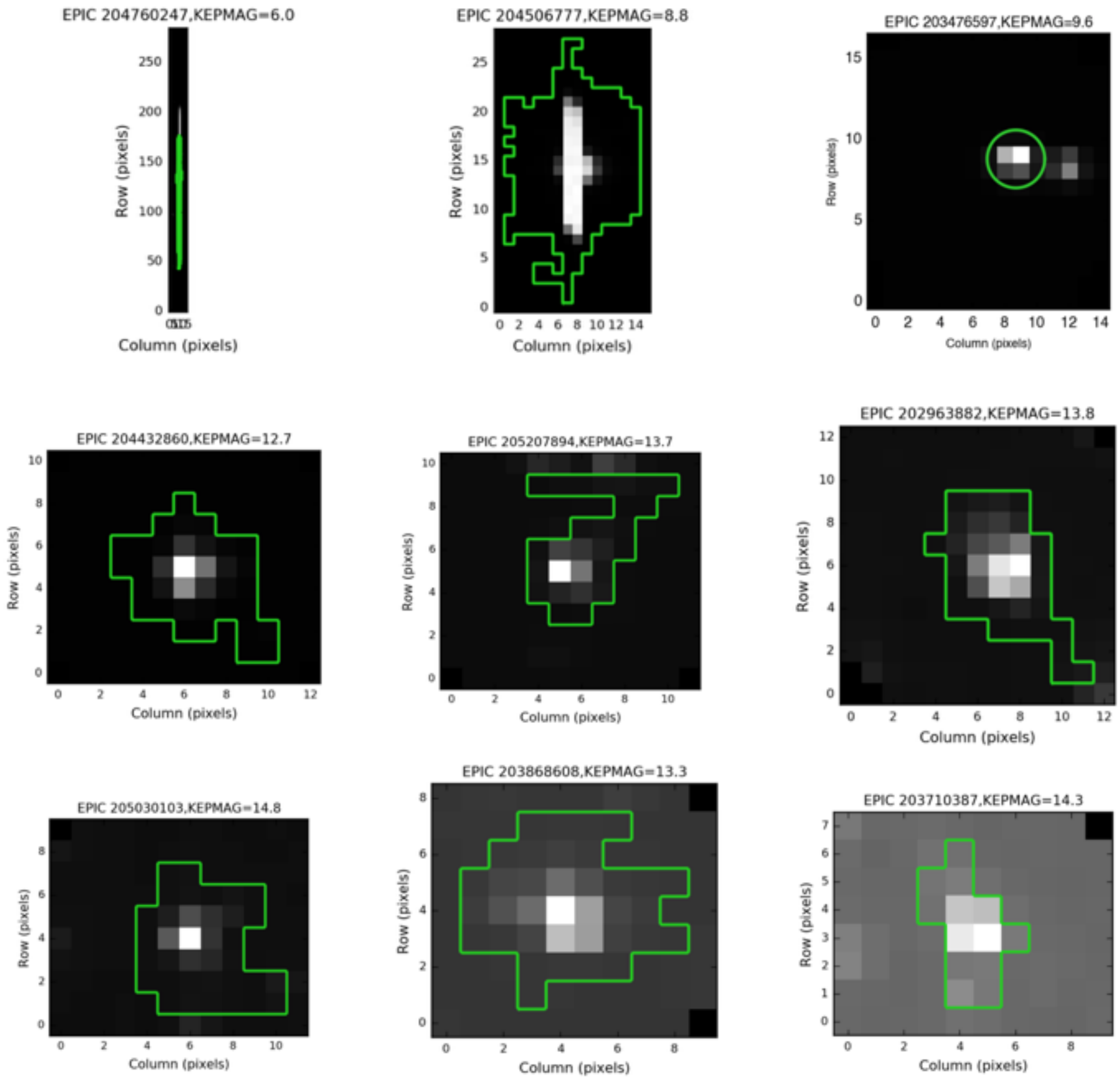


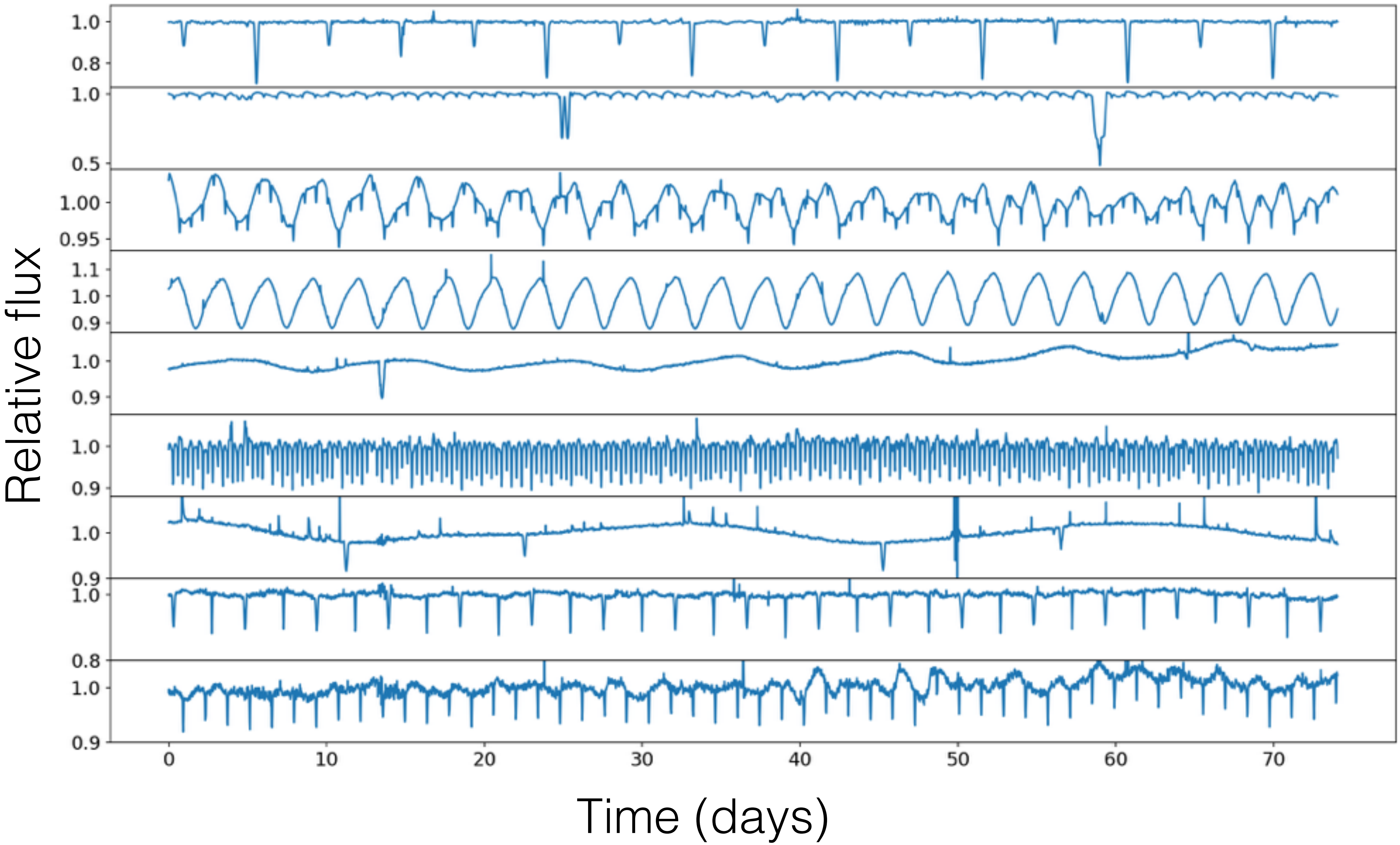
Eclipsing binary tests of pre-MS models

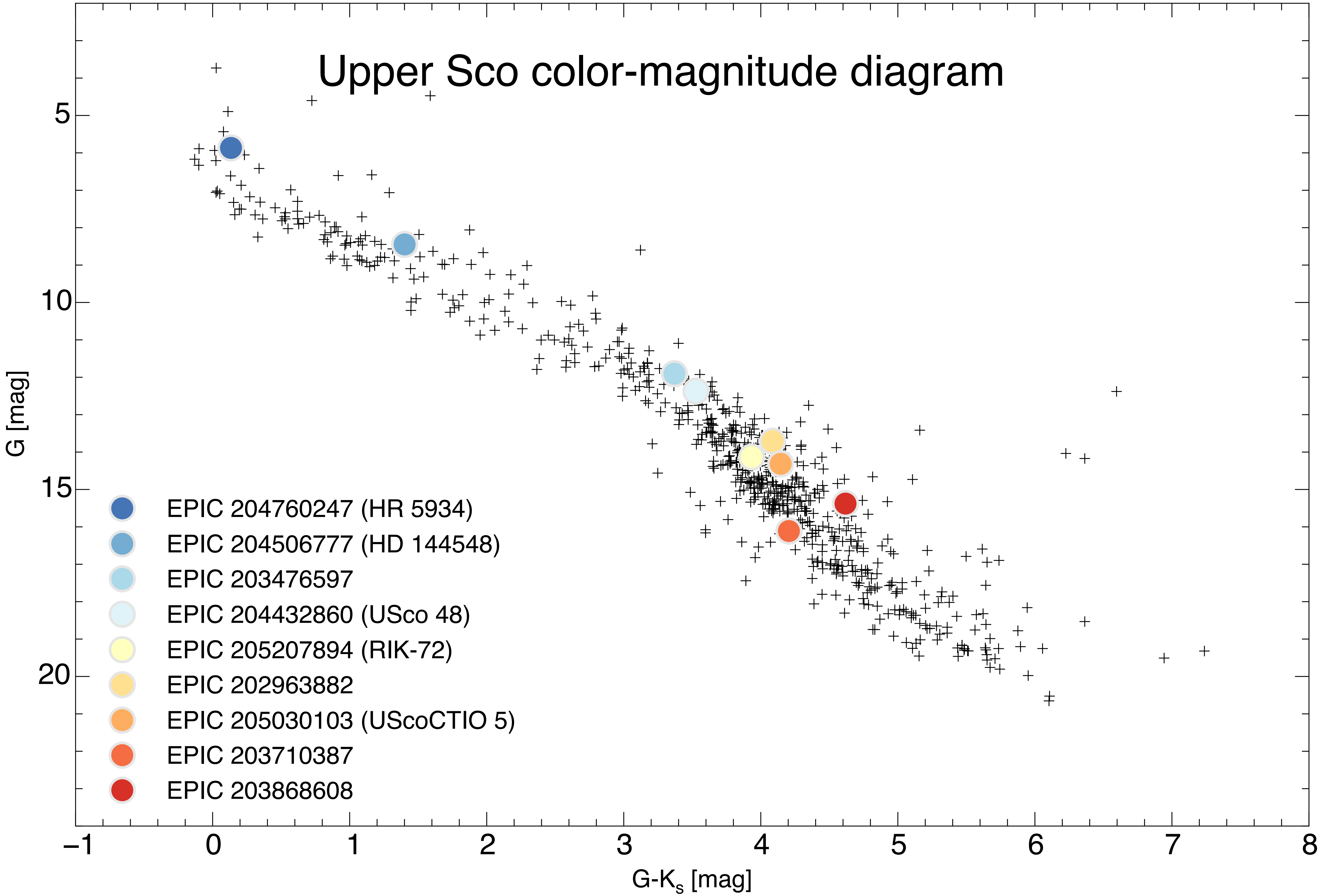


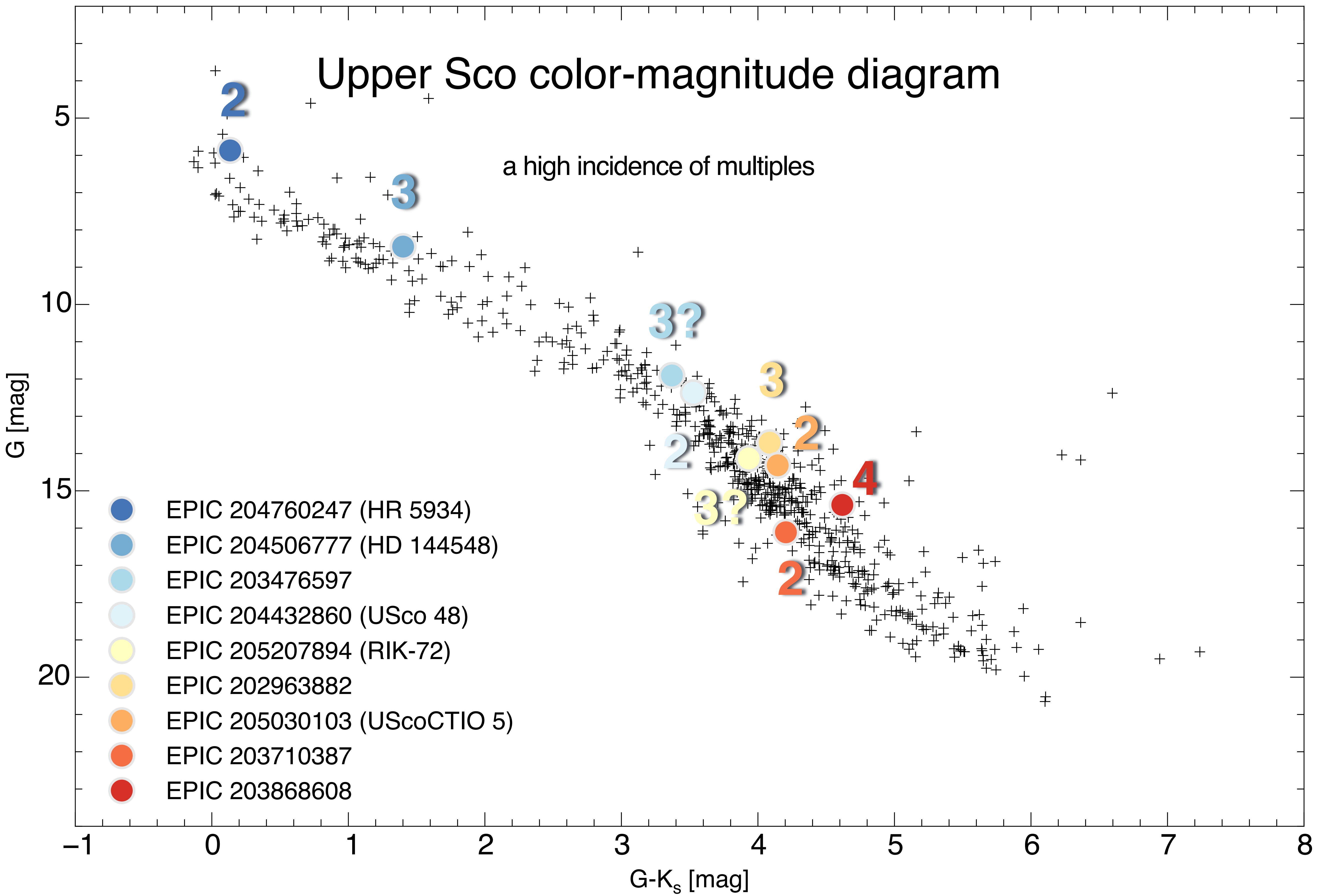
Eclipsing binary tests of pre-MS models

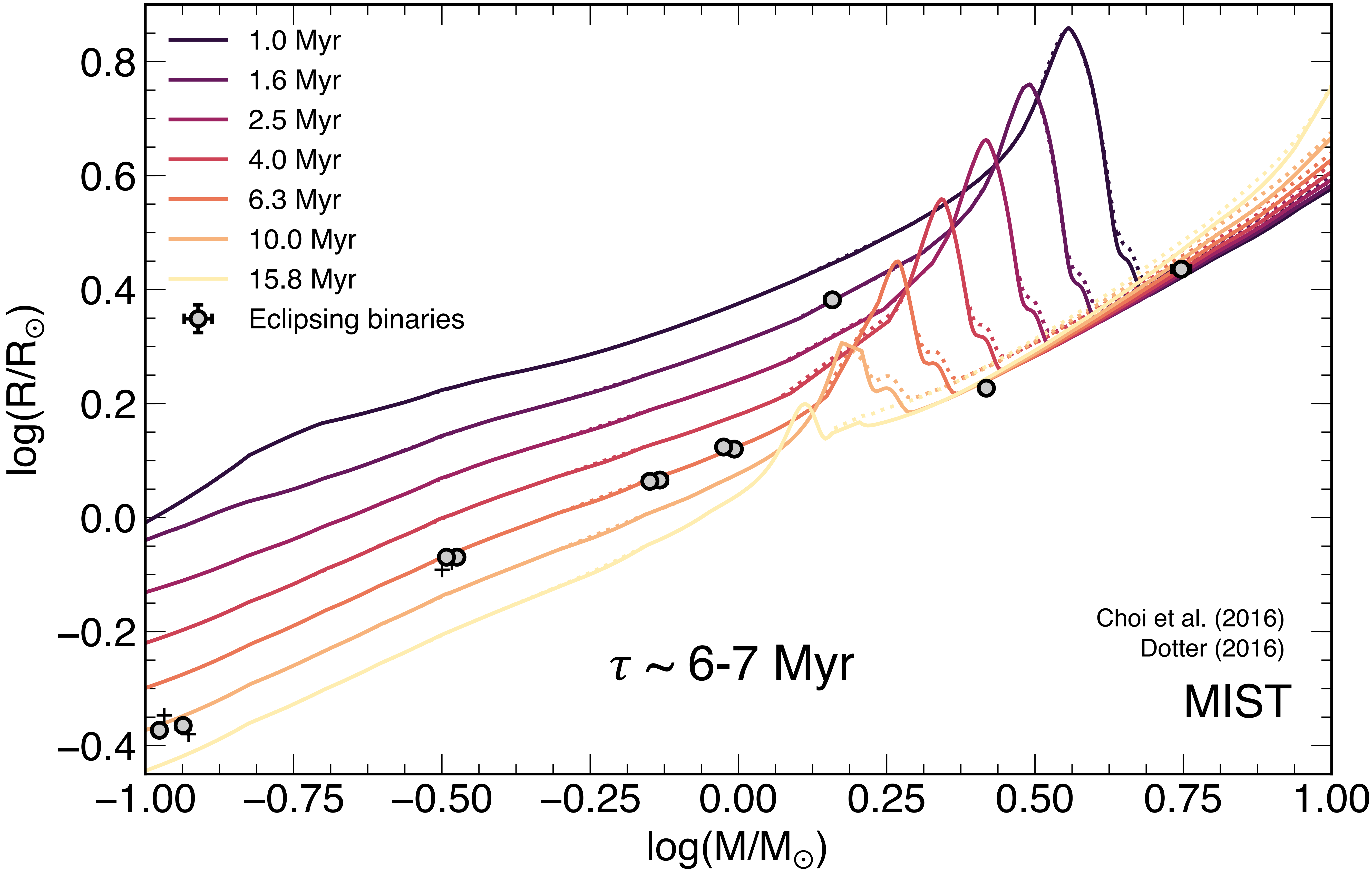



EPIC 204760247,KEPMAG=6.0
EPIC 204506777,KEPMAG=8.8
EPIC 203476597,KEPMAG=9.6
EPIC 204432860,KEPMAG=12.7
EPIC 205207894,KEPMAG=13.7
EPIC 202963882,KEPMAG=13.8
EPIC 205030103,KEPMAG=14.8
EPIC 203868608,KEPMAG=13.3
EPIC 203710387,KEPMAG=14.3
Row (pixels)
Column (pixels)

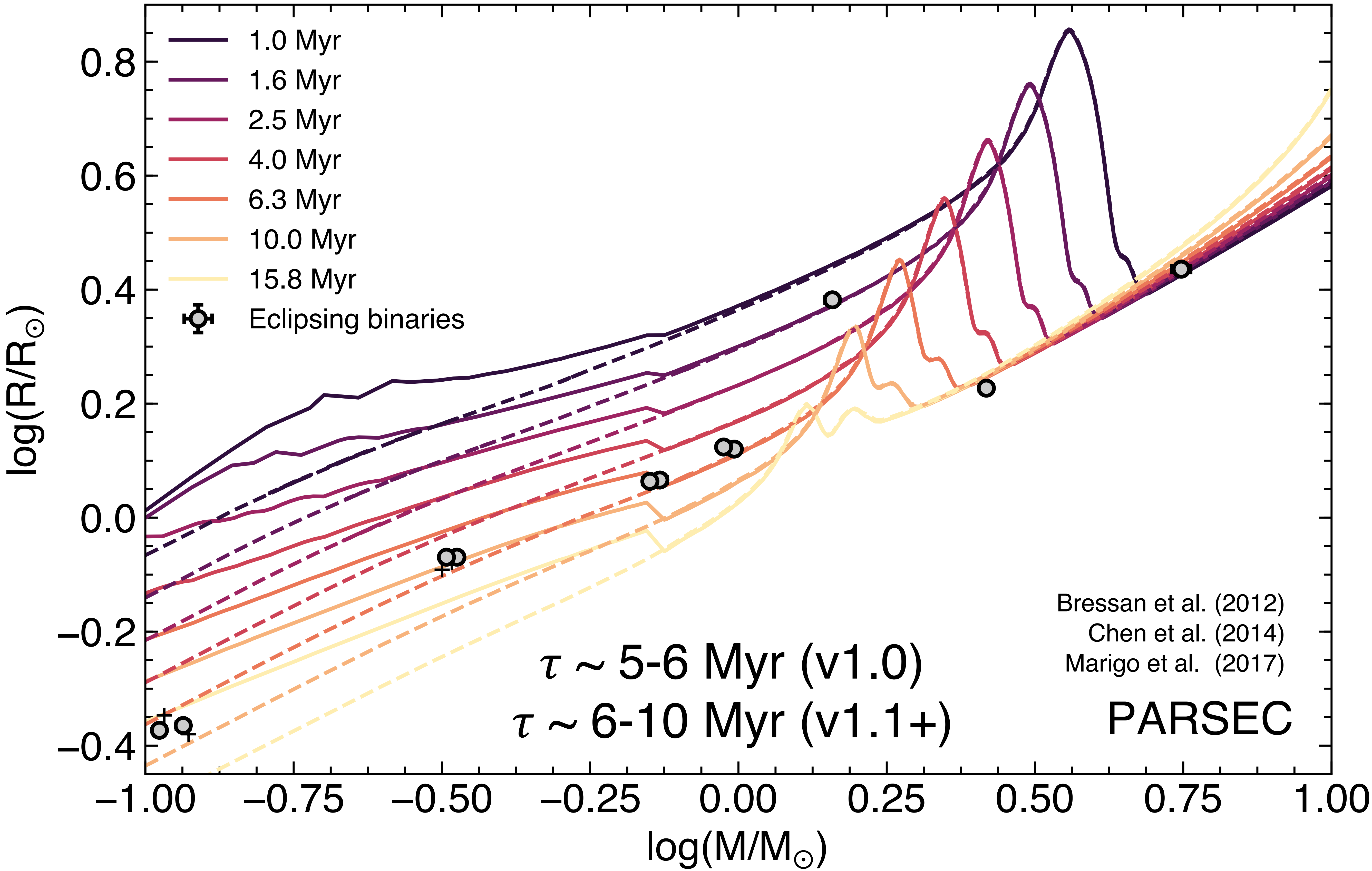

Relative flux
1.0
0.8
1.0
0.5
1.00
0.95
1.1
1.0
0.9
1.0
0.9
1.0
0.9
1.0
0.9
1.0
0.8
1.0
0.9
0
10
20
30
40
50
60
70
Time (days)

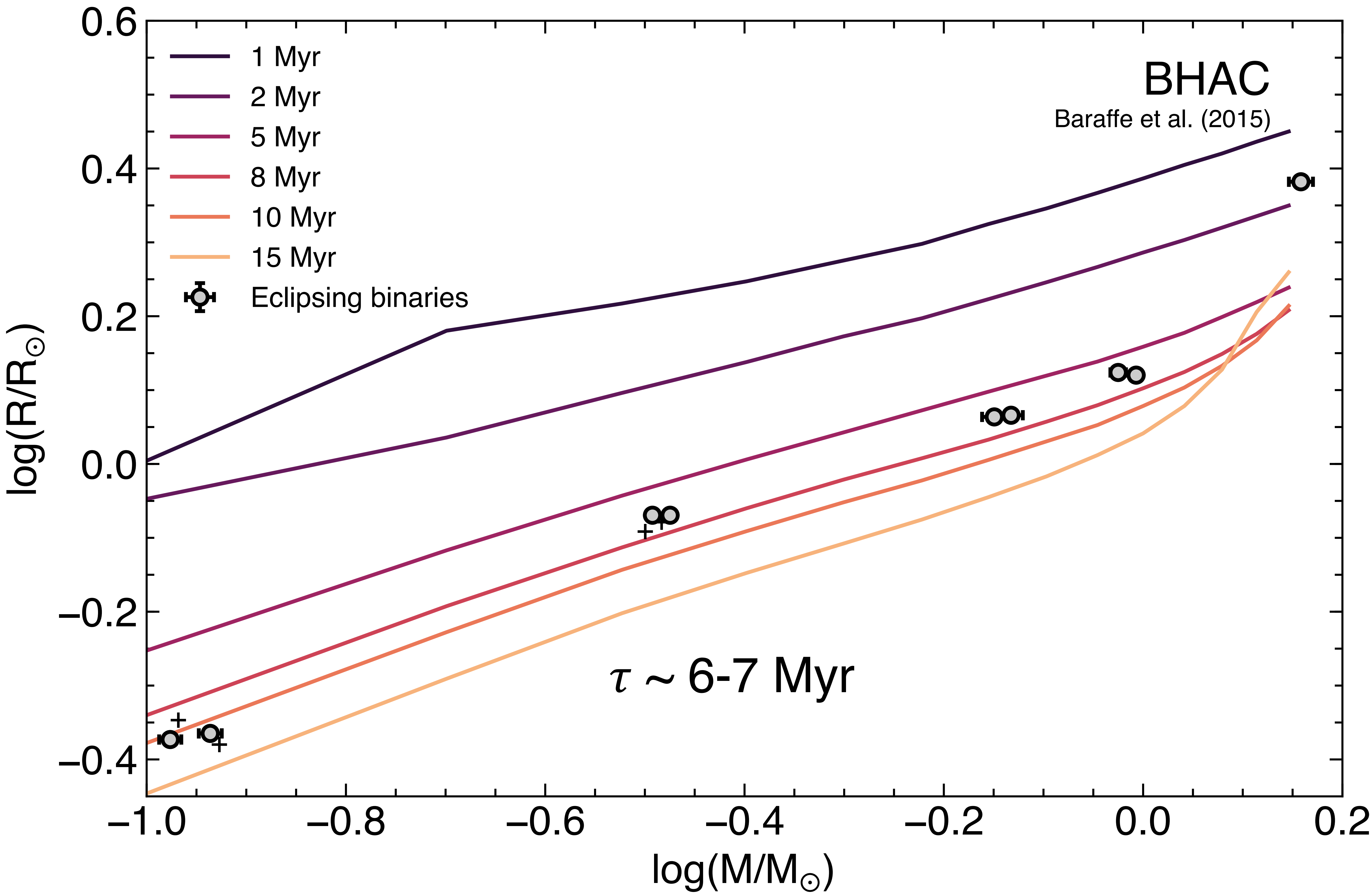

Upper Sco color-magnitude diagram
G [mag]
5
10
15
20
G-K$_s$ [mag]
−1
0
1
2
3
4
5
6
7
8
EPIC 204760247 (HR 5934)
EPIC 204506777 (HD 144548)
EPIC 203476597
EPIC 204432860 (USco 48)
EPIC 205207894 (RIK-72)
EPIC 202963882
EPIC 205030103 (UScoCTIO 5)
EPIC 203710387
EPIC 203868608


Upper Sco color-magnitude diagram
a high incidence of multiples
2
3
3?
3
2
2
4
3?
2
EPIC 204760247 (HR 5934)
EPIC 204506777 (HD 144548)
EPIC 203476597
EPIC 204432860 (USco 48)
EPIC 205207894 (RIK-72)
EPIC 202963882
EPIC 205030103 (UScoCTIO 5)
EPIC 203710387
EPIC 203868608
G [mag]
5
10
15
20
–1
0
1
2
3
4
5
6
7
8
G-K_s [mag]

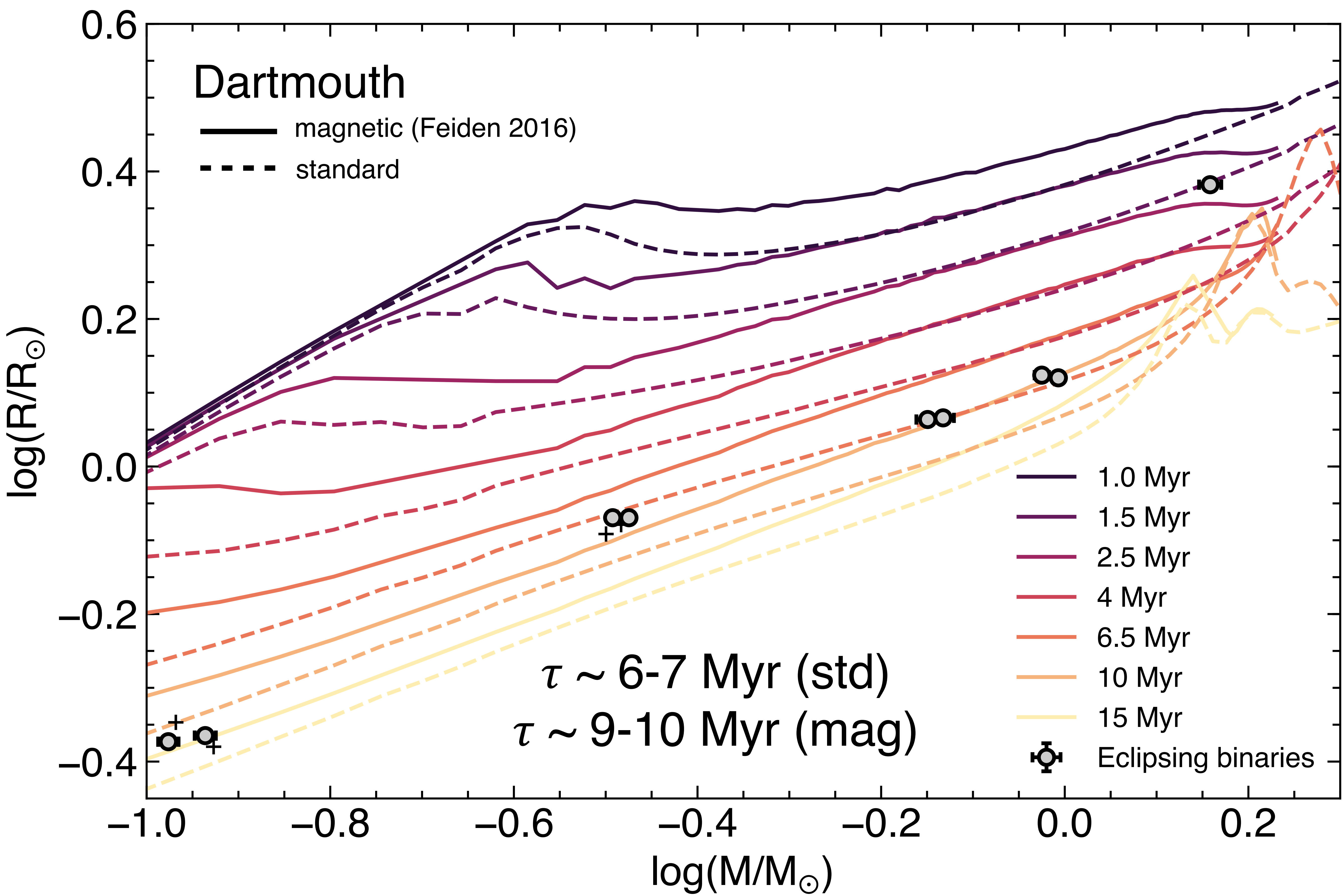


1.0 Myr
1.6 Myr
2.5 Myr
4.0 Myr
6.3 Myr
10.0 Myr
15.8 Myr
Eclipsing binaries
Choi et al. (2016)
Dotter (2016)
MIST
$\tau \sim$ 6-7 Myr
$\log(R/R_\odot)$
$\log(M/M_\odot)$
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00


1.0 Myr
1.6 Myr
2.5 Myr
4.0 Myr
6.3 Myr
10.0 Myr
15.8 Myr
Eclipsing binaries
log(R/R⊙)
log(M/M⊙)
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−1.00
−0.75
−0.50
−0.25
0.00
0.25
0.50
0.75
1.00
τ ~ 5-6 Myr (v1.0)
τ ~ 6-10 Myr (v1.1+)
Bressan et al. (2012)
Chen et al. (2014)
Marigo et al. (2017)
PARSEC

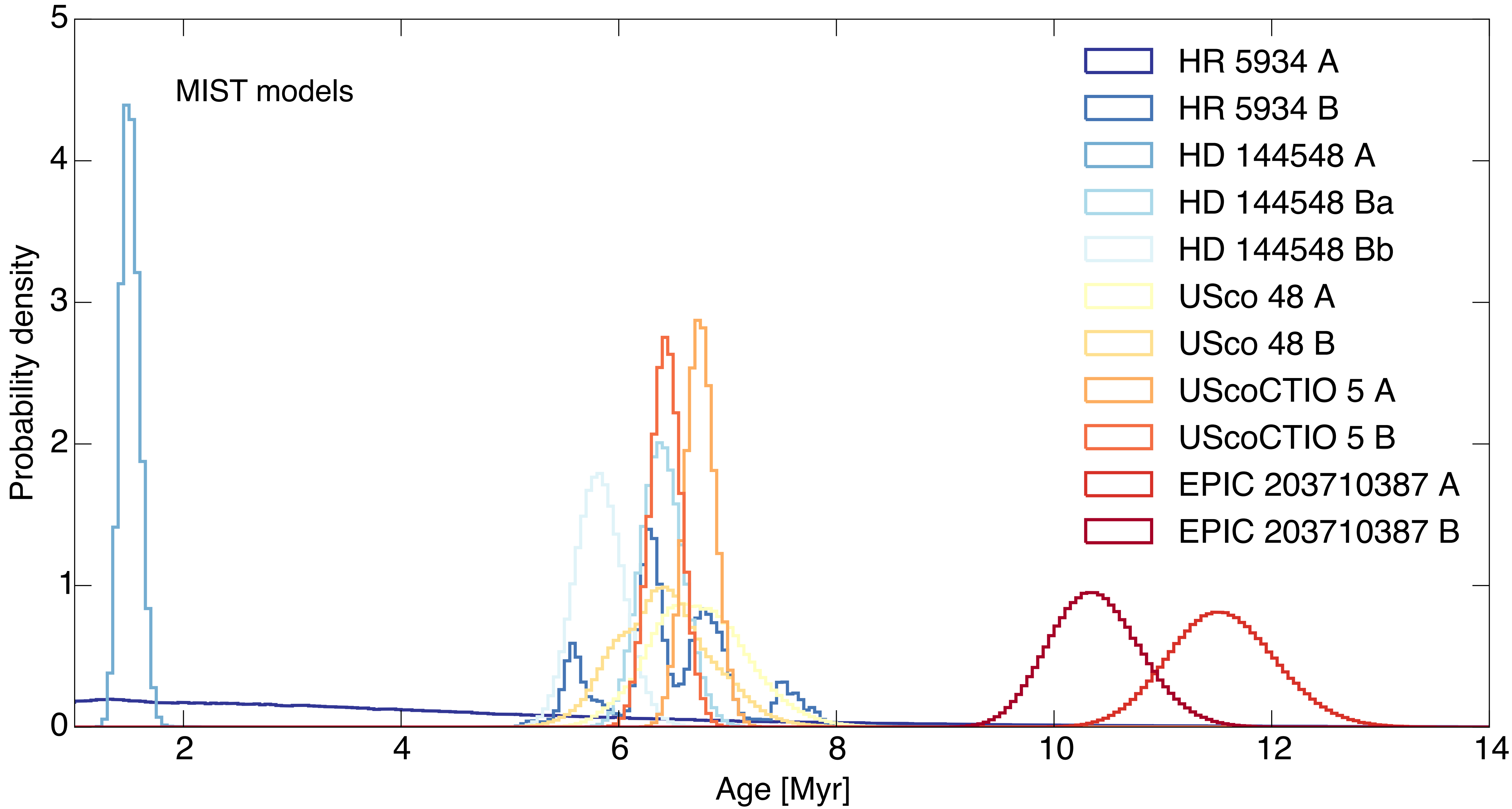


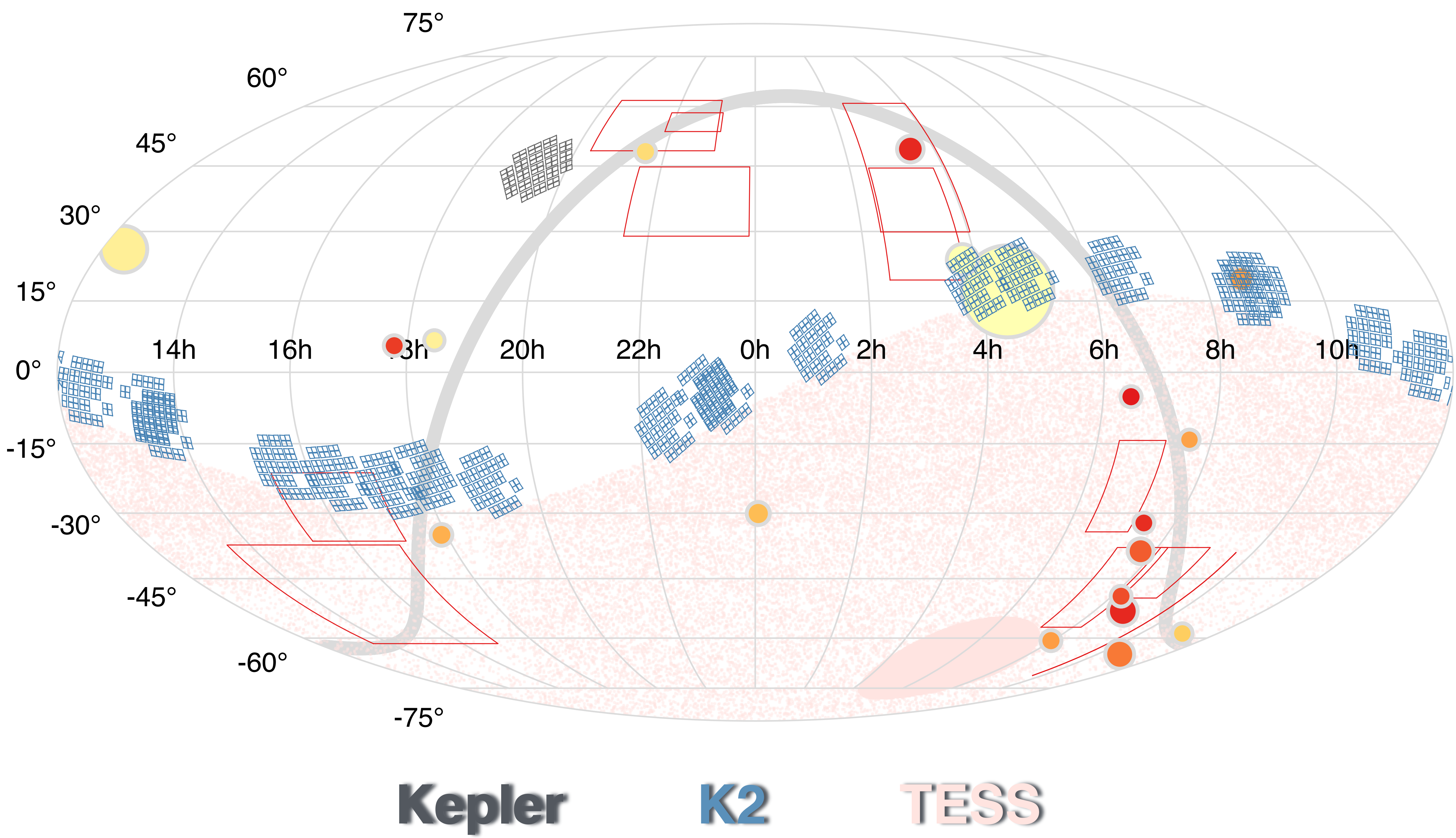
BHAC
Baraffe et al. (2015)
1 Myr
2 Myr
5 Myr
8 Myr
10 Myr
15 Myr
Eclipsing binaries
$\tau \sim$ 6-7 Myr
0.6
0.4
0.2
0.0
−0.2
−0.4
log(R/R$_\odot$)
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
log(M/M$_\odot$)



Dartmouth
magnetic (Feiden 2016)
standard
0.6
0.4
0.2
0.0
−0.2
−0.4
log(R/R$_\odot$)
−1.0
−0.8
−0.6
−0.4
−0.2
0.0
0.2
log(M/M$_\odot$)
τ ~ 6-7 Myr (std)
τ ~ 9-10 Myr (mag)
1.0 Myr
1.5 Myr
2.5 Myr
4 Myr
6.5 Myr
10 Myr
15 Myr
Eclipsing binaries

Age-dating in the mass-radius diagram





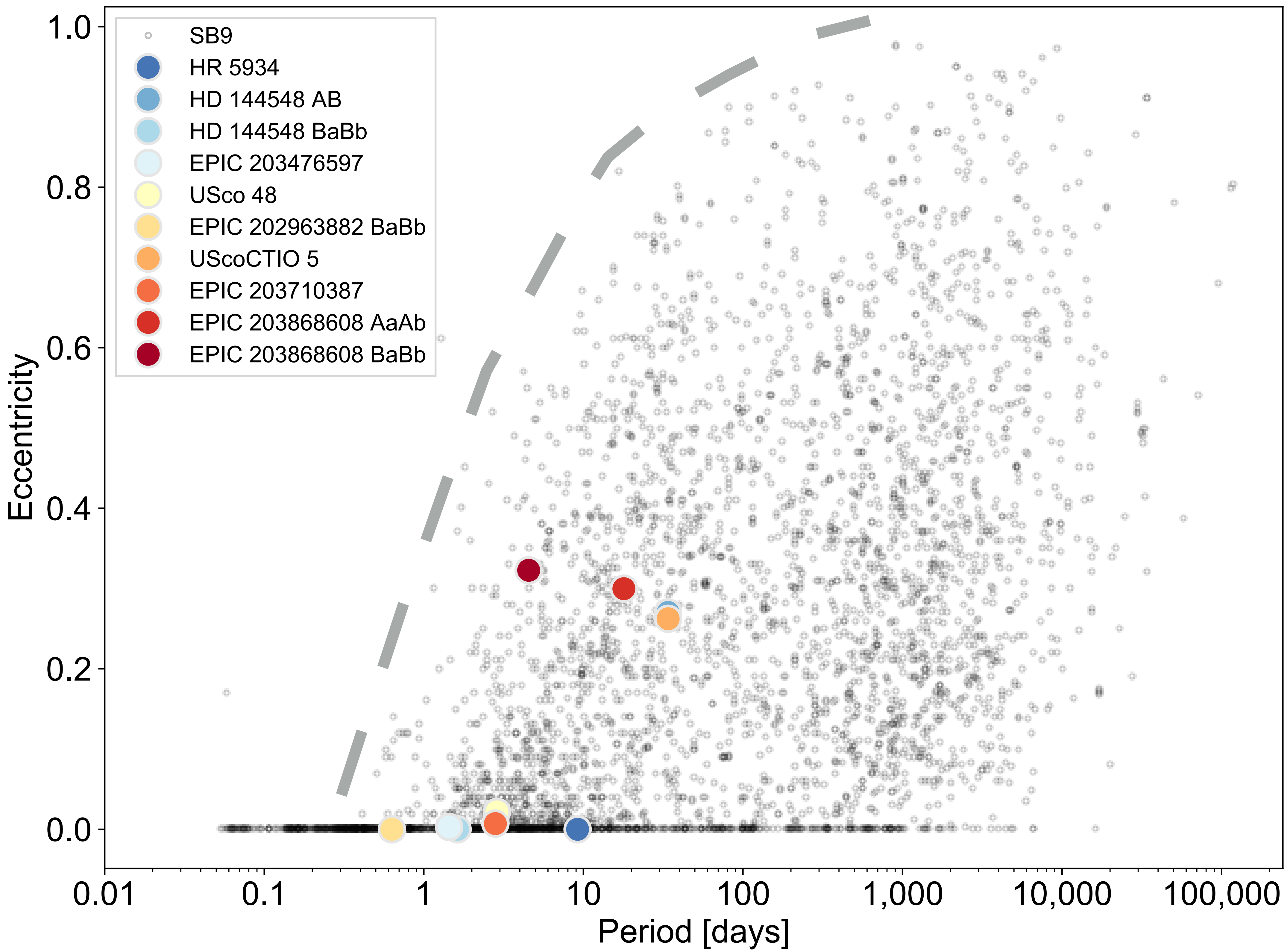
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
14h
16h
18h
20h
22h
0h
2h
4h
6h
8h
10h
Kepler
K2
TESS

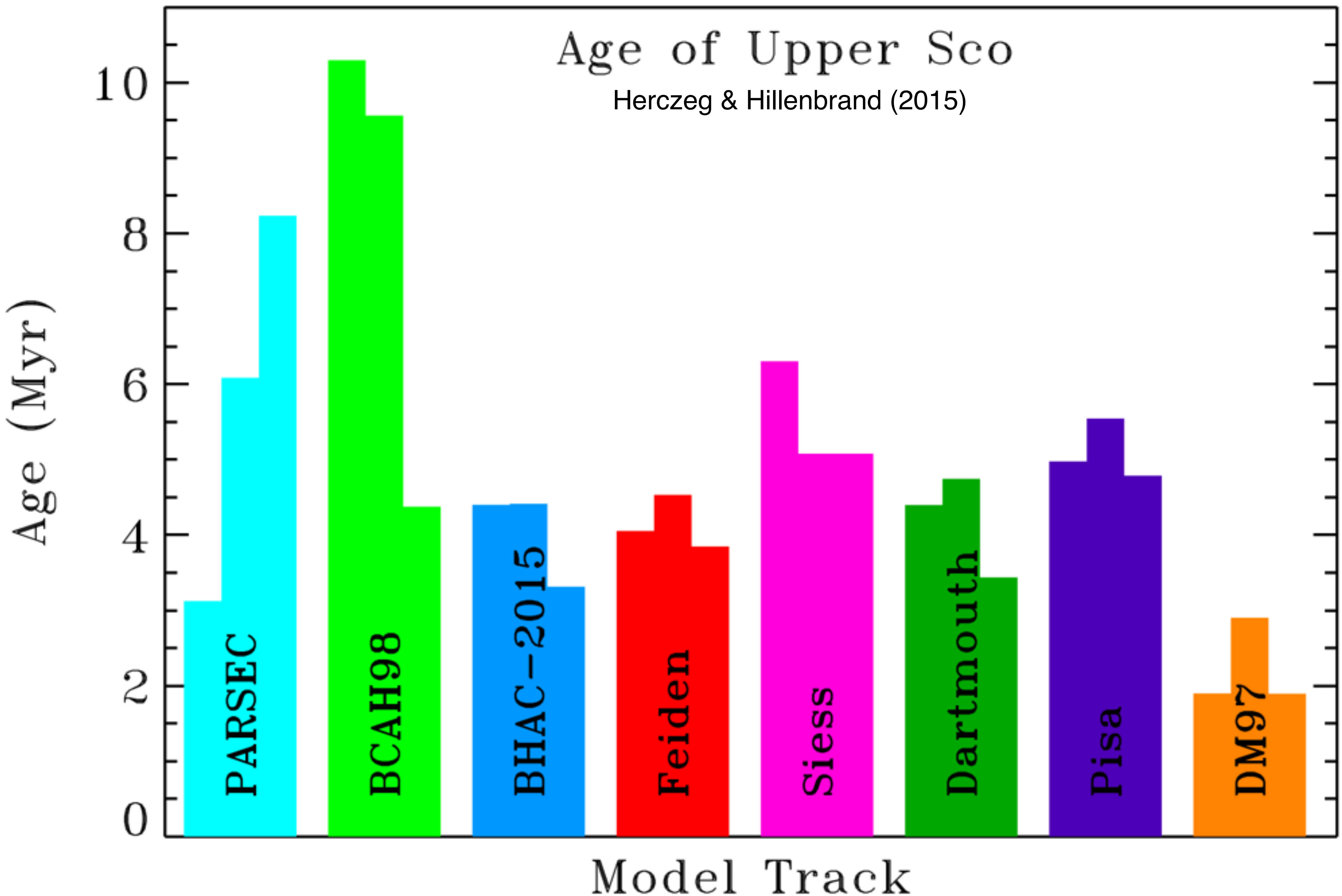
Conclusions

1. Standard models predict a fairly consistent ~6 Myr age, while magnetic models suggest an age of ~10 Myr, but require weaker fields at lower masses to fit the data
2. Standard models (BHAC15, Dartmouth, MIST) underestimate stellar masses inferred from an H-R diagram by 20—40%, *except* PARSEC which overestimate mass by >80% at lowest masses
3. Magnetic / spotted models generally fare better (fractional errors <10%)
4. Degree of disagreement depends on the empirical SpT-Teff scale adopted
5. If binaries have different accretion histories or initial angular momenta, how reliable are they for age-dating pre-MS populations?

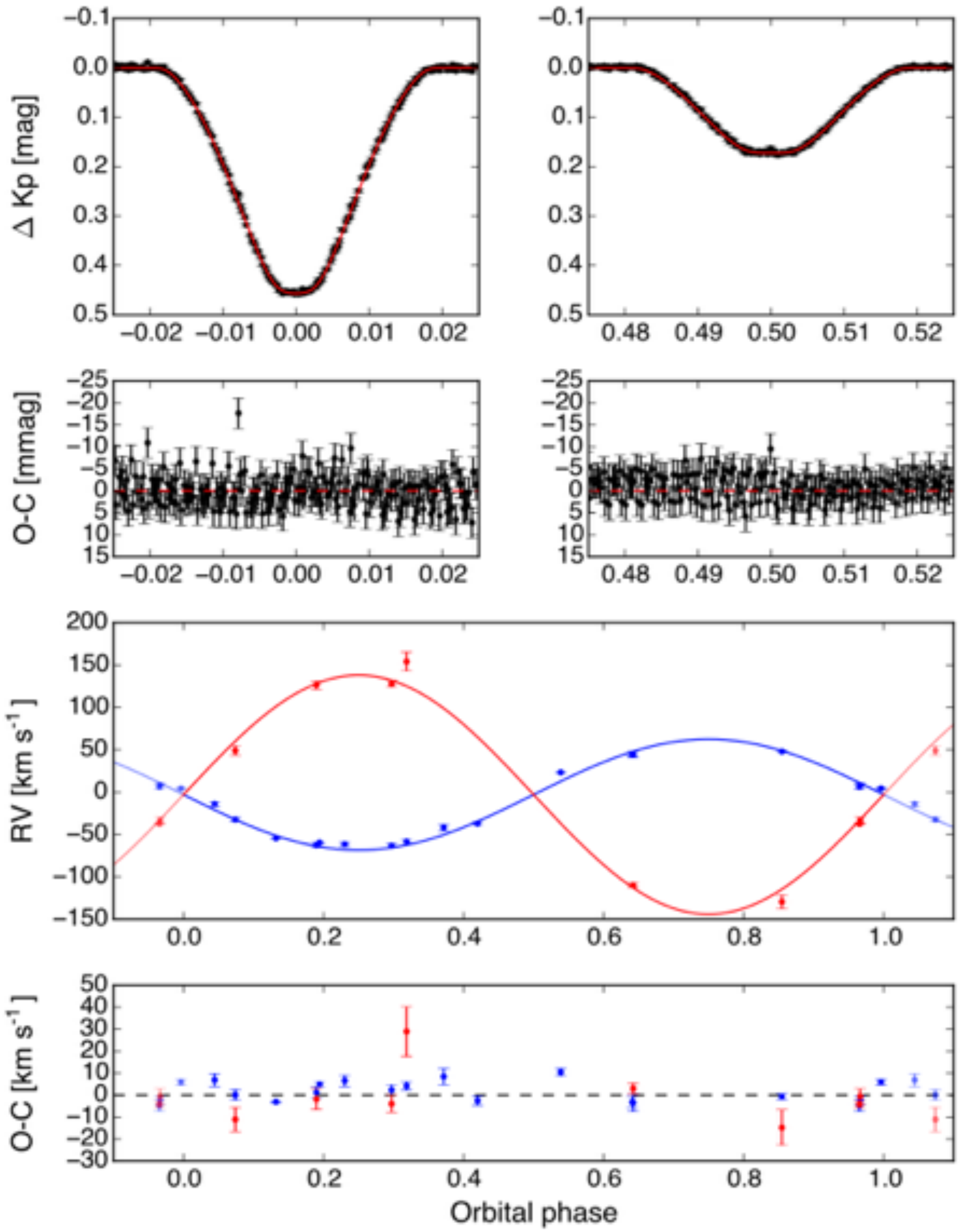
auxiliary slides

Pre-main sequence tidal dissipation




Age of Upper Sco
Herczeg & Hillenbrand (2015)
Age (Myr)
0
2
4
6
8
10
PARSEC
BCAH98
BHAC−2015
Feiden
Siess
Dartmouth
Pisa
DM97
Model Track

HR 5934



5.7 M$_\odot$ + 2.7 M$_\odot$ (±3%)

2% errors on radii

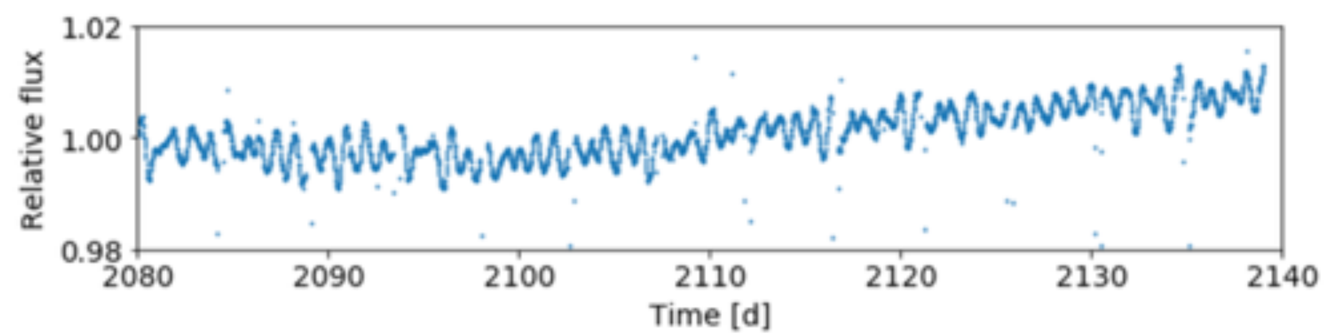
slowly rotating

Gaia DR1 distance

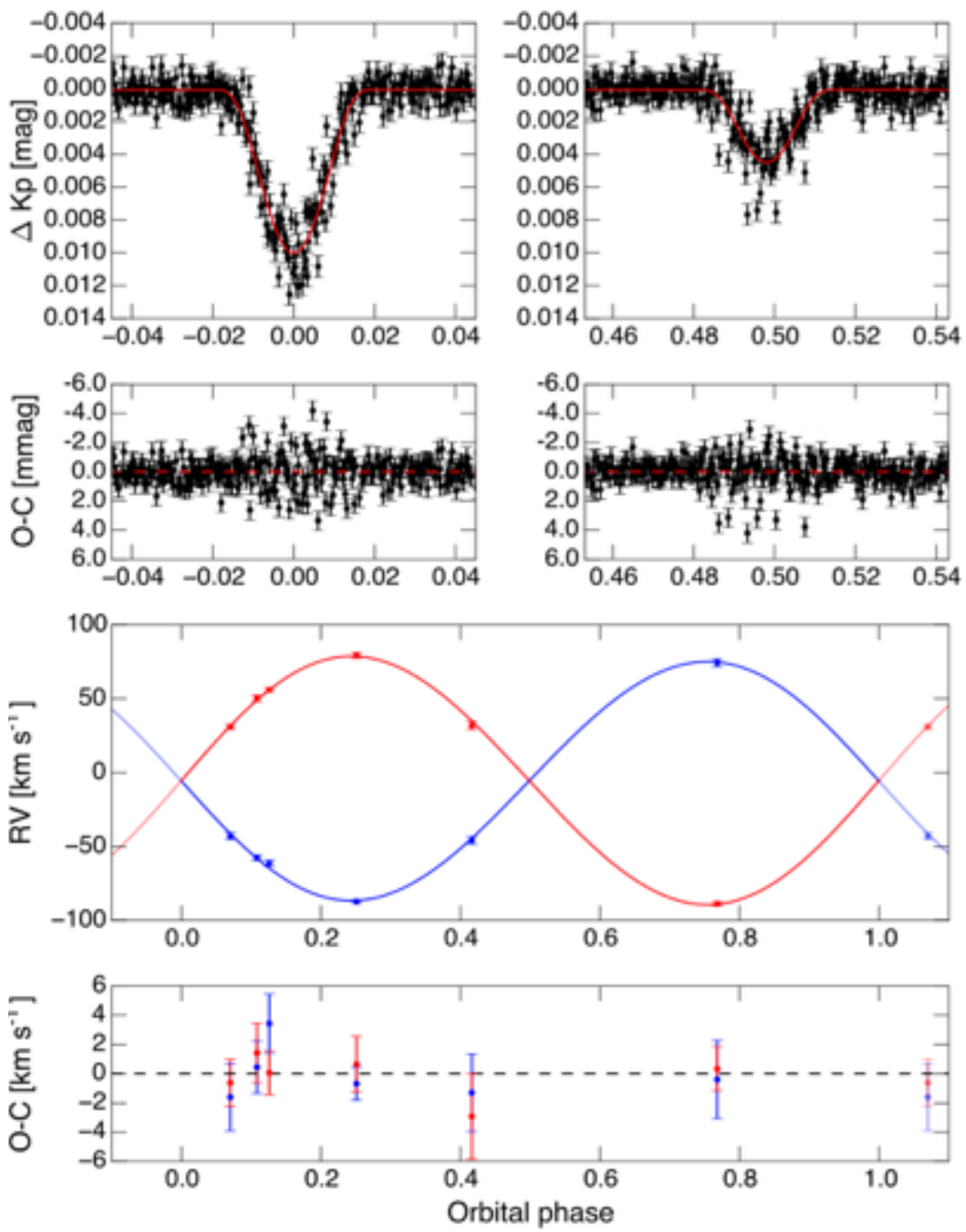
projected angular separation: 1.1 - 1.4 mas
potentially resolvable with CHARA

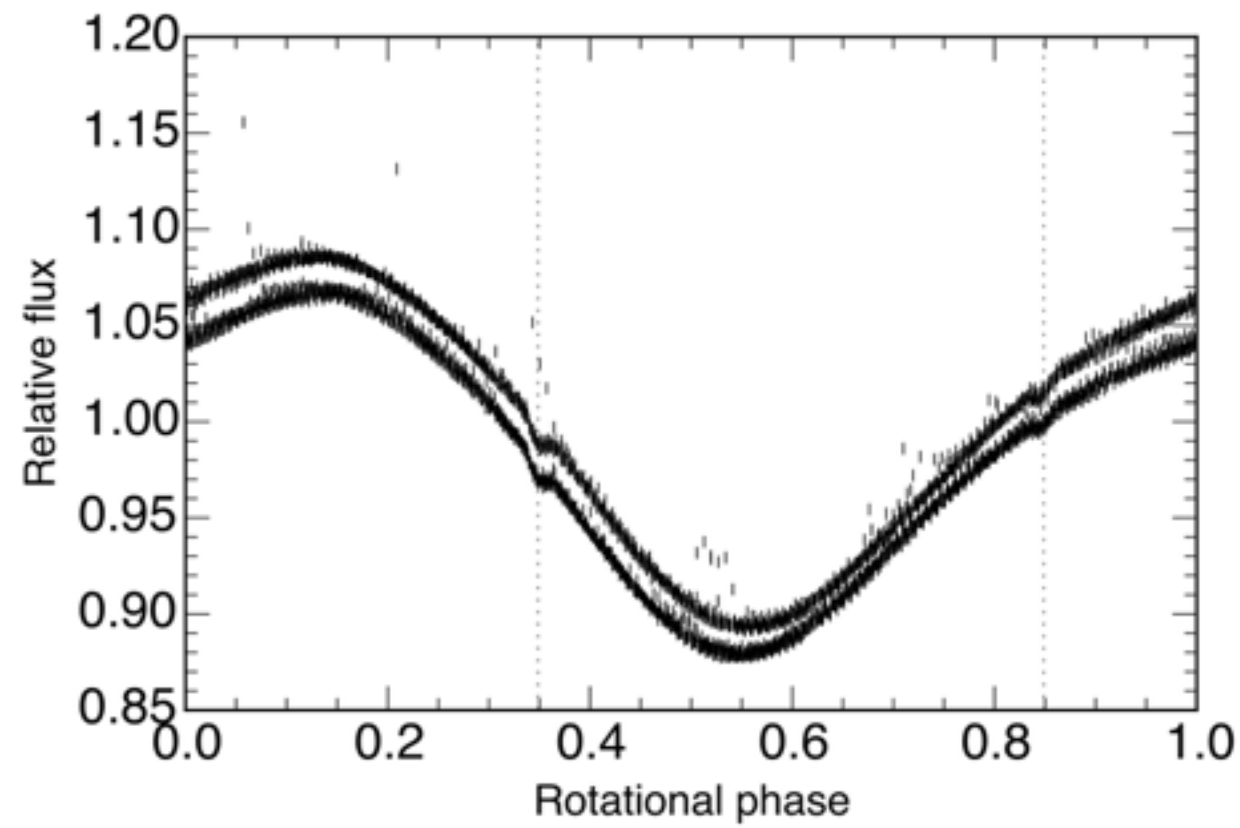
location in mass-radius
diagram effectively sets minimum age
of ~4 Myr for USco

primary is a slowly pulsating B-star



USco 48



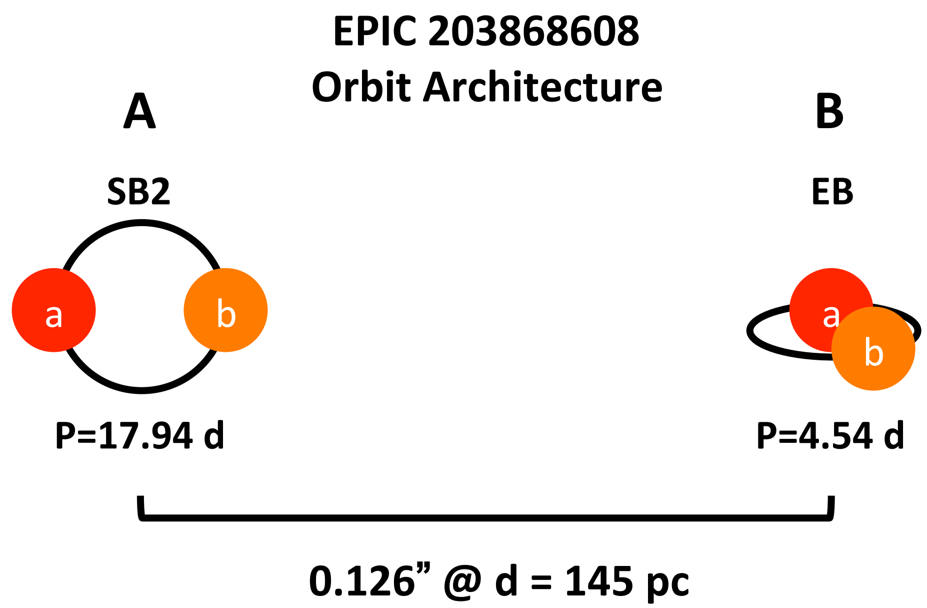


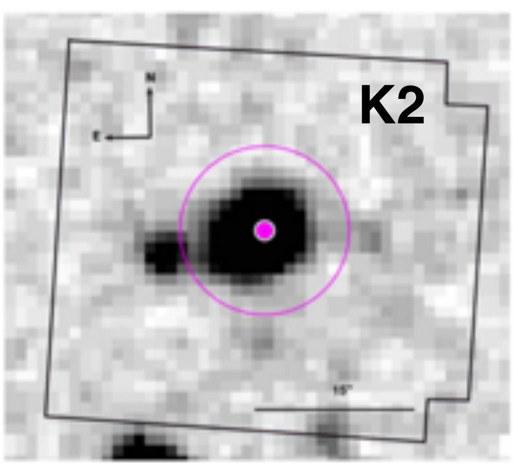
$P_{orb} = P_{rot} = 2.9$ d

synchronized, nearly circularized

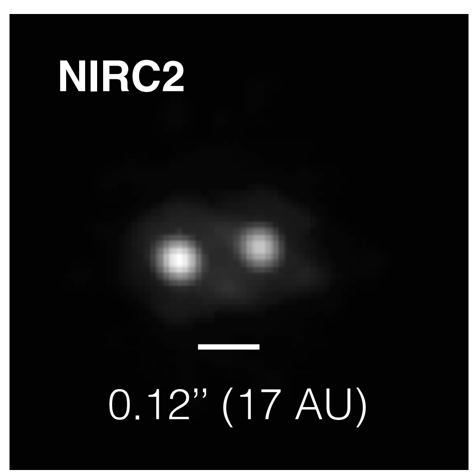
$0.74\ M_\odot + 0.72\ M_\odot$ (±3%)

EPIC 203868608: a young quadruple

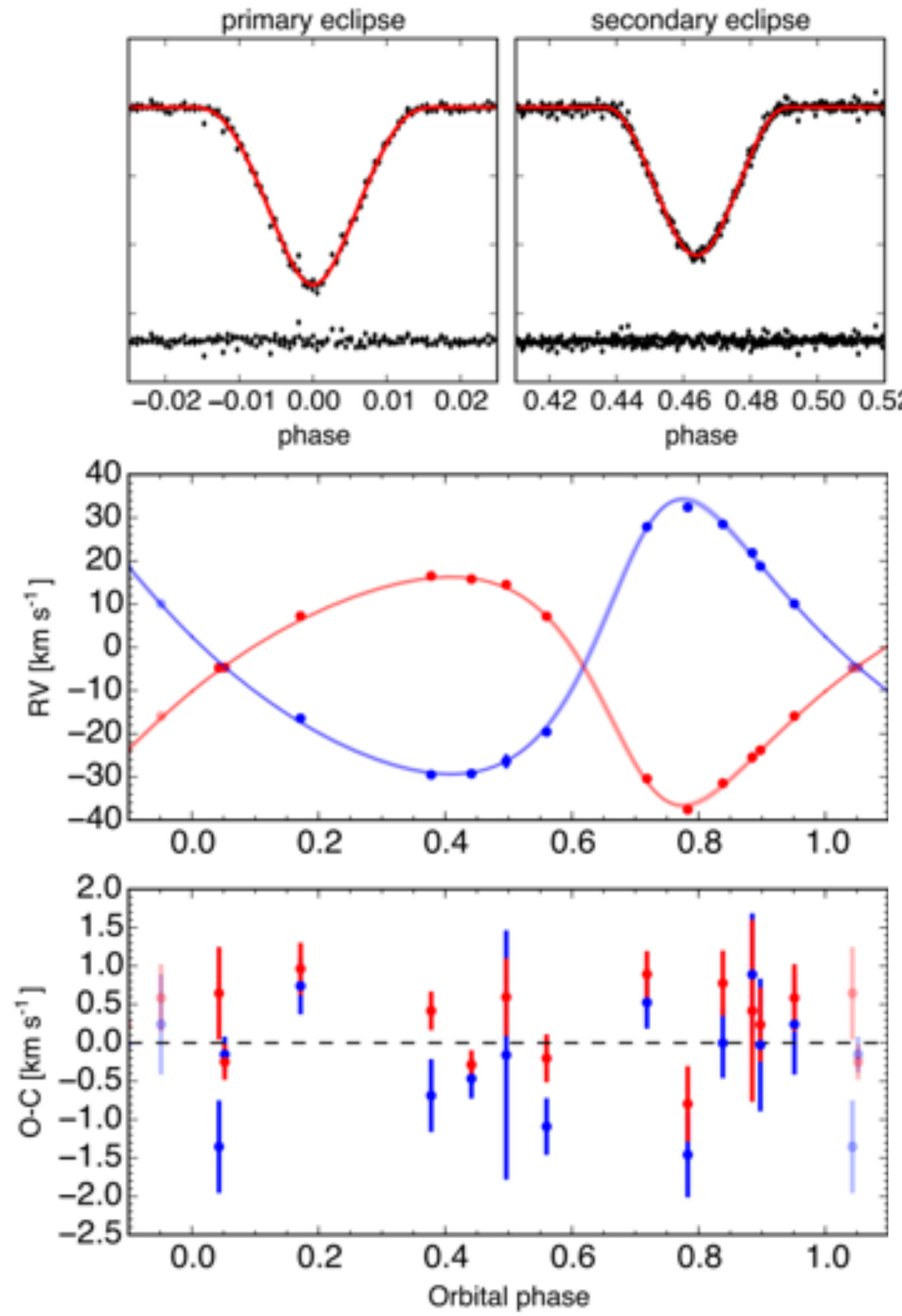




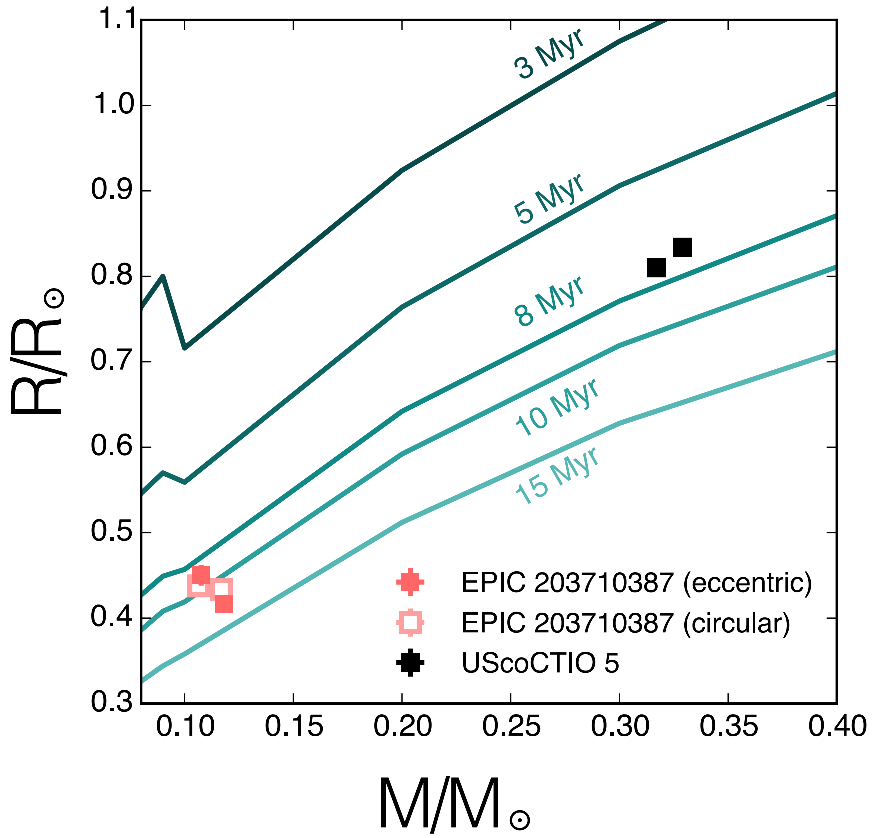
$P_{SB2} = 17.9$ d
$(M_1+M_2) \sin^3 i = 0.37\ M_\odot$



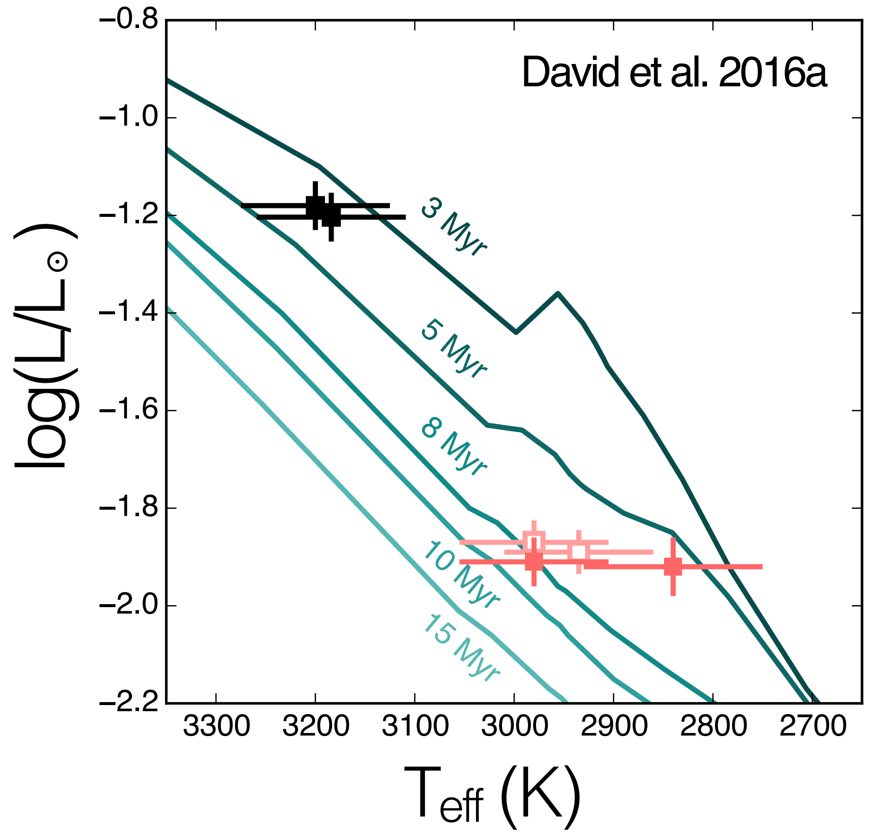
$P_{EB} = 4.5$ d
masses currently unknown
polar orbit?
(Wang, TJD et al. *in prep)*



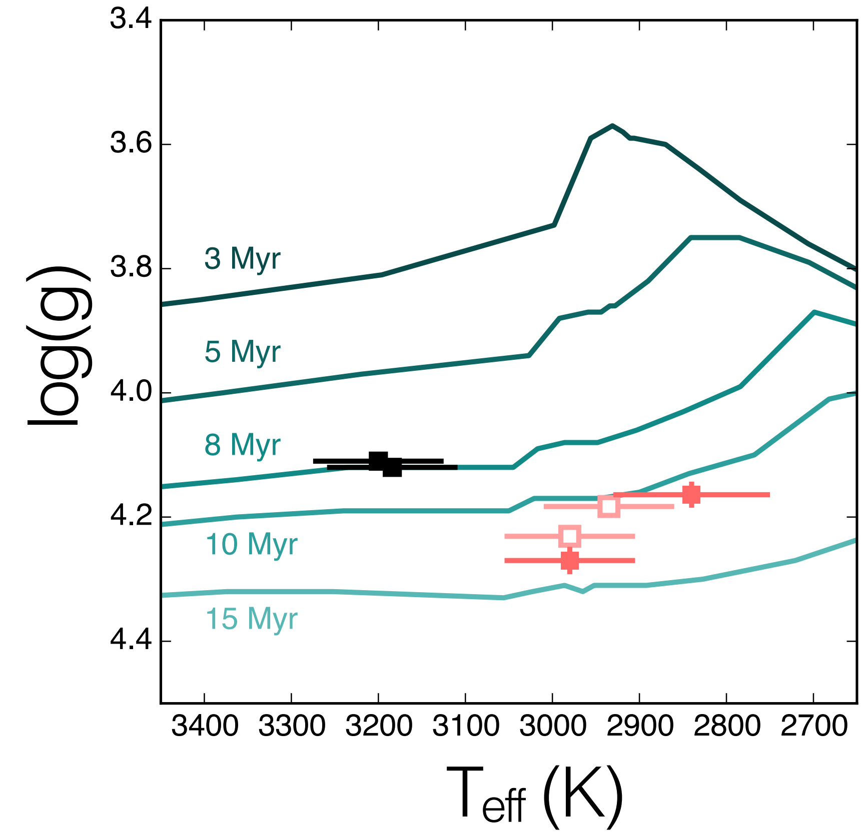
EPIC 203710387:
An eclipsing binary at the substellar boundary



10-11 Myr



7±3 Myr



>10 Myr

(1) mass dependent systematics? or evidence for an age spread?

(2) models including magnetic fields, starspots slow contraction
…which would imply this system is older

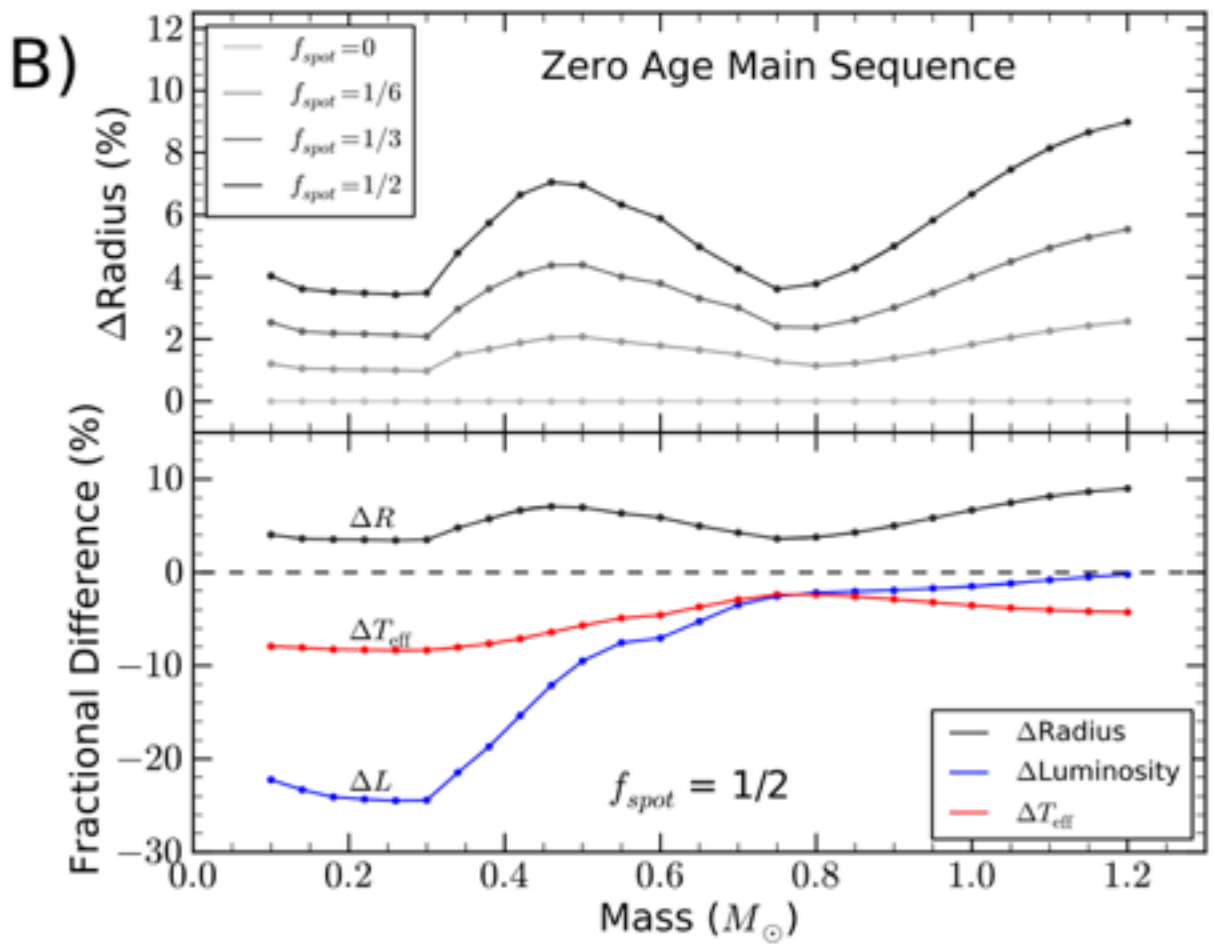
(3) the boundary between stars and brown dwarfs is SpT M5 at USco age

A history of Upper Sco age determinations

Age (Myr)	Method	Population	Year	Authors
5	kinematic	B	1964, 1978	Blaauw
5-8	kinematic, H-R diagram	BAF	1989	de Geus et al.
5	H-R diagram	BAFGKM	2002	Preibisch et al.
5 ± 3	H-R diagram	M	2006, 2008	Slesnick et al.
5 ± 3	H-R diagram	M	2008	Slesnick et al.
11 ± 3	H-R diagram	AFG	2012	Pecaut et al.
4 ± 1 (2-12)	H-R diagram	GKM	2015	Herczeg & Hillenbrand
7 ± 2	H-R diagram	B	2016	Pecaut & Mamajek
10 ± 1	H-R diagram	G	2016	Pecaut & Mamajek
5 ± 2	H-R diagram	KM	2016	Pecaut & Mamajek

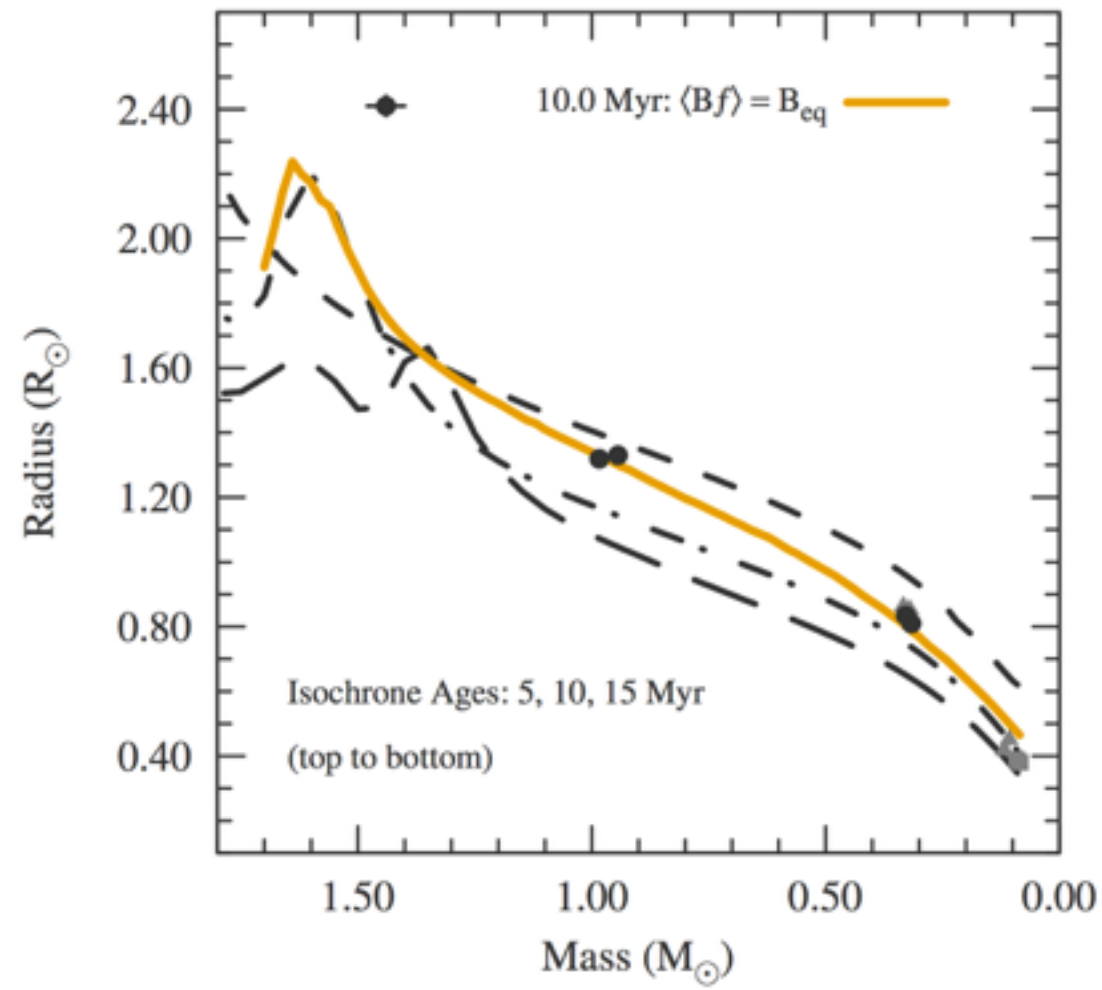
Missing physics in stellar models

Starspots



Somers & Pinsonneault (2015)

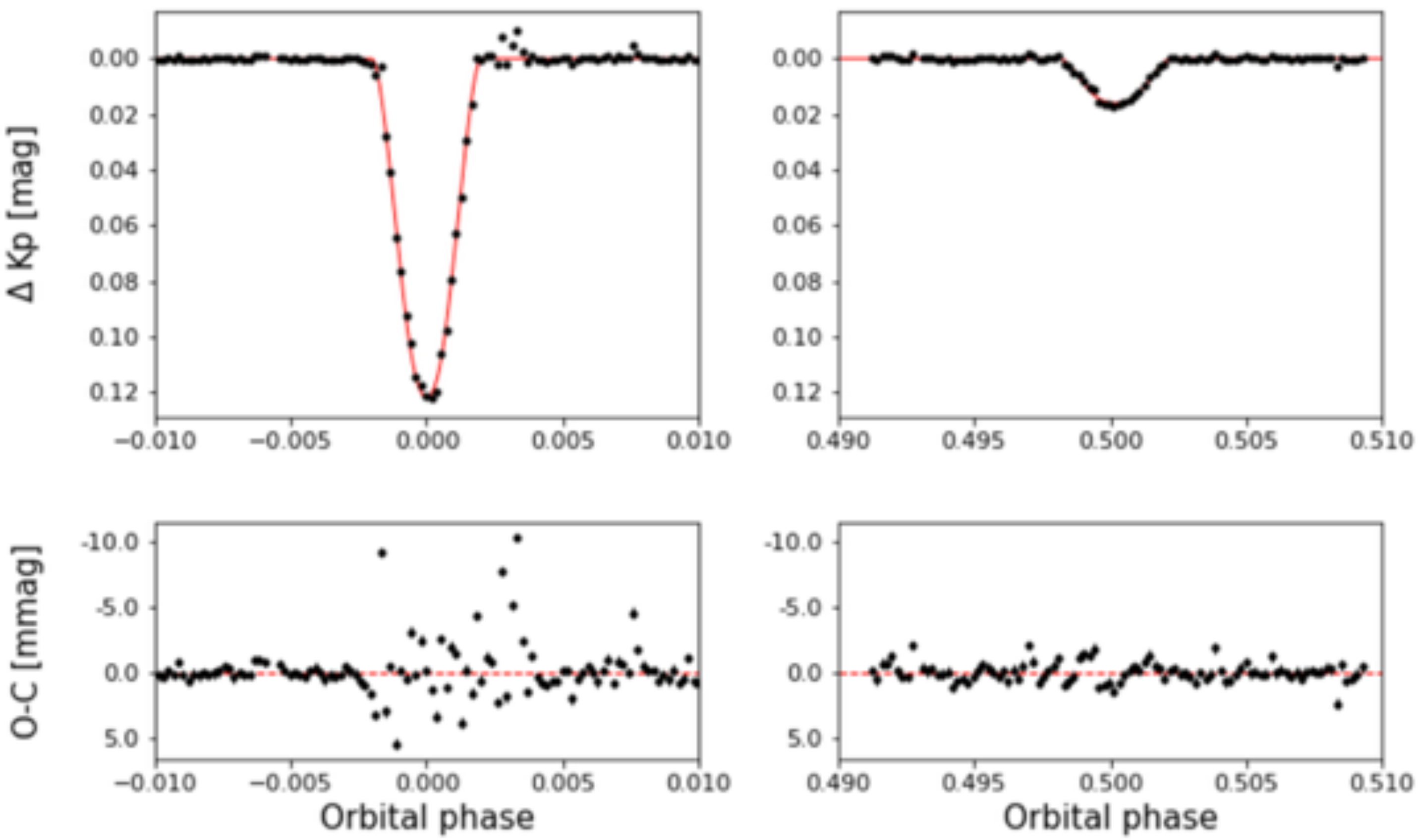
Magnetic inhibition of convection

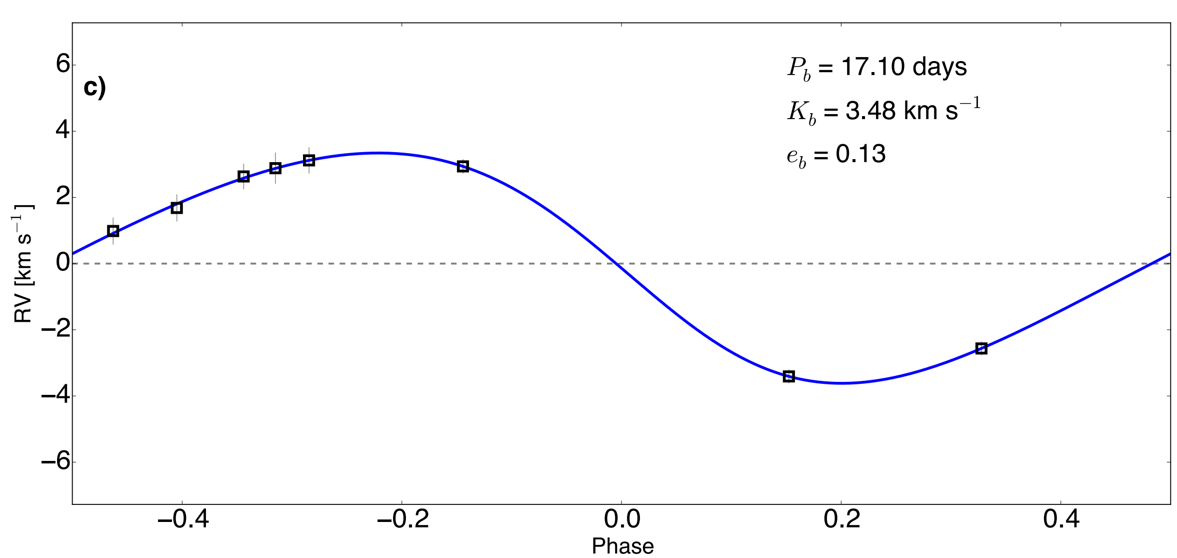


Feiden (2016)

both effects lead to inflated stellar radii, suppressed effective temperatures could imply our results are consistent with the older ~10 Myr age

RIK-72: a low-mass star with two brown dwarf companions?





primary: M2.5

P_{rot} = 10.5 d
P_{SB1} = 17.1 d
P_{EB} > 77.5 d

M_{inner} sin(i) ~ 30 M_{Jup}

T_{outer} ~ 2160 K
R_{outer} ~ 2.7 - 3.7 R_{Jup}

there must be mutual inclination